A PRELIMINARY INVESTIGATION FOR STUDY OF
GAMMA-GAMMA ANGULAR CORRELATION
IN EUROPIUM

by

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A THESIS

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PREFACE

In atomic spectroscopy the angular momentum and other
characteristics of a state are usually determined by Zeeman
effect studies. In nuclear spectroscopy, at the present, it
is entirely unfeasible to separate the nuclear magnetic sub-
states by application of external fields (Deutsch and Brady, 6).
Therefore, it is hoped that angular correlation will provide
the tool for nuclear spectroscopy that the Zeeman effect has
provided for atomic spectroscopy.

INTRODUCTION

It was first suggested by Dunworth (7) and theoretically substantiated by Hamilton (10) that when two gamma-rays are emitted in sucession by a nucleus their directions are not independent.

Consider a nucleus which passes from an excited level A to the ground level C, by way of a definite intermediate level B and the two gamma-rays which are emitted in succession in this transition A→B, B→C. If one considers only one transition, either A→B or B→C, then the angular distribution of the emitted radiation is isotropic. However, in the angular correlation process the angular distribution of one radiation is observed when it is known that the other has a fixed direction. This prescription of a fixed direction determines a polar coordinate system and defines the nuclear magnetic substates of the intermediate level B. If the orientation of the nucleus is not disturbed during the life of the intermediate state then each nuclear magnetic substate emits anisotropically but on summing over these substates with equal populations and random (relative) phases, so that the sum is incoherent, the total intensity is independent of angle. However, if one observes the first gamma-ray to be emitted in a fixed direction the probability of the intermediate state being any one of the possible nuclear magnetic substates is no longer the same as in the absence of this information. In particular this asserts that these magnetic substates are not uniformly populated.

Consequently the radiation subsequently emitted will not be isotropic (Rose and Biedenharn, 11).

This discussion and the existence of a correlation may be clarified by use of a simple example. Assume the spins of the three levels A, B, C to be 0, 1, 0 respectively. Then the two successive transitions are both dipoles. For the first transition there are three possibilities $\Delta m = +1, 0, -1$, all of which are equally probable. If the first transition is $\Delta m = 0$ then it must be followed by a second transition in which $\Delta m = 0$ and if the first transition is $\Delta m = \pm 1$ then it must be followed by a second transition $\Delta m = \pm 1$. Since the choice of a direction is arbitrary, let this direction be chosen such that it is parallel to the direction of emission of the first gamma-ray. Therefore, the first transition can not lead to the intermediate state B with magnetic quantum number $m = 0$ since a dipole emission with $\Delta m = 0$ does not give rise to any radiation along this chosen direction. This leads one to conclude that the first transition must then be of the type $\Delta m = -1$ or $\Delta m = +1$ and the second transition must be of the type $\Delta m = +1$ or $\Delta m = -1$, respectively. Either of these second transitions will give rise to a directional distribution of the second gamma-ray and therefore an angular correlation (Blatt and Weisskopf, 2).

This angular correlation is described by a function $W(\alpha)$ which gives the relative probability that the second quantum will be emitted at an angle α with the first; $W(\alpha)$ is determined by the angular momenta of the three levels A, B, C involved

in the two successive transitions, $A \rightarrow B$, $B \rightarrow C$, and by the multipole order of the radiation emitted in these transitions. Since $W(\alpha)$ does not depend upon the parity of the three levels it is impossible to distinguish between electric and magnetic radiation of the same multipole order (Frauenfelder, 9).

Specifically, the probability, per unit solid angle, that two successive gamma-rays are emitted at an angle α may be expressed most conveniently in terms of a Legendre polynomial expansion and is proportional to

$$(1) \qquad W(\alpha) = 1 + \sum_{k=1}^{m} A_{2k} P_{2k}(\cos \alpha)$$

where m is the order of the lowest multipole in the cascade (Frauenfelder and Lawson, 8). Thus if both gamma-rays in the cascade are quadrupoles then

$$(2) \qquad W(\alpha) = 1 + A_2 P_2(\cos \alpha) + A_4 P_4(\cos \alpha).$$

The experimental procedure is to adjust two spectrometers so that each will monitor one of the gamma-rays of the cascade and measure the number of coincidences in the same period of time as the angle α , between the lines joining the detectors with the source, is varied. One of the spectrometers, usually fixed with respect to the source, serves to define the polar axis referred to above. The coincidence circuit insures that the gamma-rays detected in the second spectrometer are truly in cascade with those detected in the first spectrometer. The experimentally measured correlation can then be expressed in terms of Legendre polynomials by means of the least square fit

of the assumed form of the function; in the particular case where both gamma-rays are quadrupoles the assumed form would be equation (2). The resulting coefficients A_{2k} can then be compared with the theoretical values given by Rose and Biedenharn (11) thus determining the values of the angular momenta of the three levels involved.[1]

The purpose of this thesis is not to determine the angular momenta of a gamma cascade but rather to provide the information required such that angular correlation experiments could be performed to determine angular momenta.

INTRODUCTORY DISCUSSION

Electronic Instruments

The electronic instruments used for the collection of the experimental data consisted of two scintillation spectrometers and a coincidence counter. Each spectrometer consisted of a crystal detector, a pulse height analyzer, a high voltage power supply, and a scaler. For a complete discussion of the operational features of these electronic instruments the reader is referred to the thesis by Butler (3), pp. 4-20.

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[1]This is true only for centered point sources and point detectors and will be clarified under the discussion of angular efficiency curves.

Stability of the Electronic Equipment

When a measurement of the coincidence count is made at a
particular angle it is important that the electronic instruments
remain stable to insure that the peak of the gamma-ray does not
shift with respect to the channel level setting during the time
the measurement is taken. Relatively small fluctuations in the
high voltage power supply cause the peak of the gamma-ray signal
voltage to shift. Therefore, the high voltage power supply
was connected to a line voltage stabilizer and a fan was placed
beneath the power supply to increase its stability. Stability
tests were then made over different time intervals. Detectable
shifts of gamma-ray voltage peak were found to occur after a
period of about two hours. This feature set an upper limit on
the time that a measurement of the coincidence count at a partic-
ular angle could be taken.

Magnetic Field Quenching

Originally, the research for this thesis was performed in
the fringing fields of beta-ray spectrometers. Both spectrom-
eters contained permanent magnets with strong fields. It was
found that magnetic field quenching of the crystal detectors
took place when the detectors were in the proximity of the
magnets. Therefore, these magnets were demagnetized to eliminate
any effects the magnetic field had on the detectors.

APPARATUS, SOURCE, AND SOURCE HOLDER

For the purpose of measuring the variation in the coincidence count with variation of the angle between the crystal detectors, a platform was constructed upon which one of the crystal detectors could be rotated about a source while the other crystal detector remained fixed. Plate I is a photograph of the apparatus and source holder.

This platform consisted of a plywood disk approximately 62 cm in radius. Situated on this disk were two carriages, one of which was rigidly connected to the disk while the other was free to rotate about a pivot which consisted of a lucite rod 2.54 cm in diameter. Throughout the construction of this apparatus, metal was avoided as much as possible to decrease the scattered radiation. Scattering of radiation in the material near the detectors can simulate a correlation (Frauenfelder, 9).

Each crystal detector was mounted on a semicircular support and attached to the carriage in such a manner that the support was free to move radially with respect to the source along the carriage but was restricted from any sideward motion with respect to the carriage. This arrangement allowed the detectors to be moved various distances from the source.

Each carriage had a ruler connected to the side of the carriage and a pointer connected to the crystal detector to provide a measurement of the distance from the source to the face of the scintillation crystal.

A strip of sheet metal aluminum was rigidly attached to

EXPLANATION OF PLATE I

Photograph of the fixed and moveable crystal detectors,
apparatus, and source holder.

A1, A2......Scalers
B1, B2......Pulse Height Analyzers
C1, C2......High Voltage Power Supplies
D...........Fixed Crystal Detector
E...........Moveable Crystal Detector
F1, F2......Semicircular Supports
G1, G2......Carriages

PLATE I

9

A2

B2

C2

D
F2
G2

A1

B1

C1

E
F1
G1
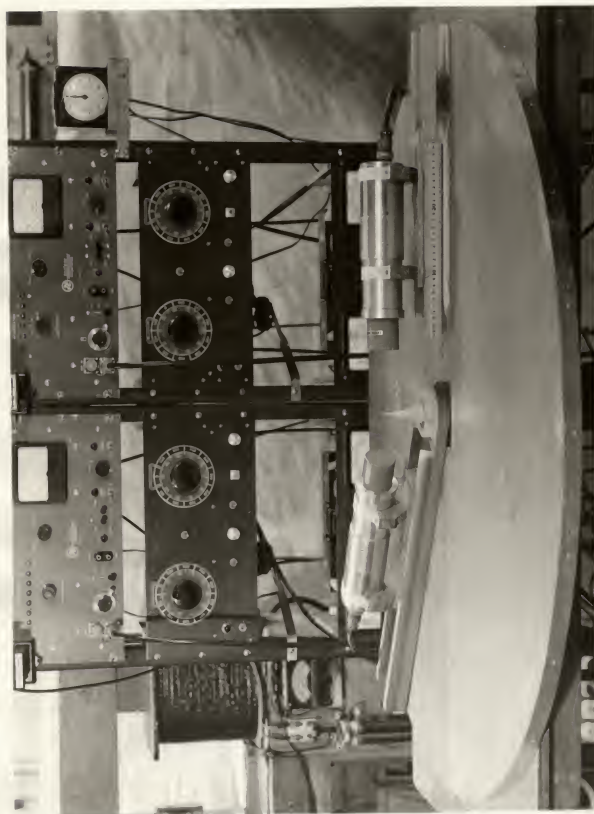
the perimeter of the disk. This aluminum strip was marked every 15°, starting with the midpoint of the fixed crystal detector, so that a measurement of the coincidence count could be taken every 15°.[1] The moveable carriage had a set screw fastened at the extreme of the carriage next to the perimeter of the disk, thus allowing the carriage to be firmly fixed in position for a measurement of the coincidence count at a particular angle.

For this research the source consisted of a small piece of pile irradiated europium. The natural isotopes are Eu^{151} (47.77 percent) and Eu^{153} (52.23 percent). Eu^{152} may by beta decay be transformed into Sm^{152} and Gd^{152}. These daughter nuclei are not generally in the ground state but rather in some excited state immediately following the beta disintegration. Subsequently, they may decay to the ground state by gamma emission. The decay schemes of Sm^{152} and Gd^{152} are presented in Plate II. These decay schemes proposed by Cork et al (4) were derived through the use of the separated isotopes of europium.

The emission of two gamma-rays in rapid succession from an excited nucleus is termed a gamma cascade. The two gamma cascades which were of interest in connection with these angular correlation experiments were the 244-122 kev cascade of Sm^{152}

[1] In these experiments, the coincidence count is observed at 15° intervals, starting with an angle of 90° and ending with an angle of 270° with respect to the fixed crystal detector.

EXPLANATION OF PLATE II

Decay schemes of Sm^{152} and Gd^{152} proposed by Cork et al and derived from

the separated isotopes of europium. The dotted transitions are not well

established. Energy values are in Mev.

PLATE II
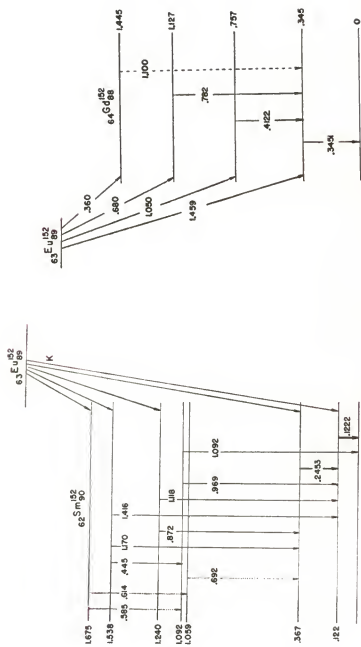
and the 778-344 kev cascade of Gd^{152}. These two cascades may be seen in Plate II.

The shape and relative size of the source holder is shown in Plate I. The source holder was constructed of lucite and rigidly mounted on the moveable carriage. The cylindrical part of the source holder, which contained the source, had an inner radius of 1 mm and was 1 mm thick.

The source holder was constructed so that it was symmetrical about its longitudinal axis and carefully centered, with respect to the two detectors, when it was mounted on the moveable carriage. These two precautions were taken since a slight assymetry in the source position will affect the observed correlation (Deutsch and Brady, 6).

PARAMETER CURVES

When using the electronic instruments it was found very useful to be able to find within a few tenths of a volt the channel level setting where a gamma-ray of a particular energy would be located.

The high voltage of the power supply is continuously variable from 500-1500 volts. This makes it possible to expand the spectrum for resolution or compress it for definition. When the high voltage is changed the channel level voltage where a particular gamma-ray will be located is changed. Therefore, a relation between the energy of a gamma-ray, the high voltage of the power supply, and the channel level voltage

was needed.

The graphs[1] shown in Plates III and IV provided such a relationship for the fixed and moveable detectors respectively. The graphs are a plot of the channel level voltage versus gamma-ray energy with the high voltage of the power supply as a parameter. Only those values of high voltage and gamma-ray energy have been plotted which were of interest in connection with these experiments.

RESOLVING TIME VERSUS TRUE COINCIDENCES

The resolving time of the coincidence circuit may be changed by discrete steps as the differentiator knob setting is changed. The different knob settings correspond to different values of resistors in the coincidence differentiator circuit. The values of resolving time available in this way vary from slightly less than a half microsecond to slightly less than three microseconds.

The true coincidences were obtained by first correcting the observed coincidences for the loss due to the mechanical rachet-type counter of the coincidence circuit and then subtracting the accidental coincidences which were due to the randomness of the pulses entering the coincidence circuit. A discussion of these corrections has already been given by

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[1]Since the data for the graph of Plate IV were taken, vacuum tubes have been replaced in the scintillation spectrometer. This has caused the high voltage parameter of the graph to be shifted downward by approximately 50 volts.

EXPLANATION OF PLATE III

Graph showing the relation between the location and
energy of a gamma transition when the high voltage of the
power supply, used with the fixed crystal detector, is used
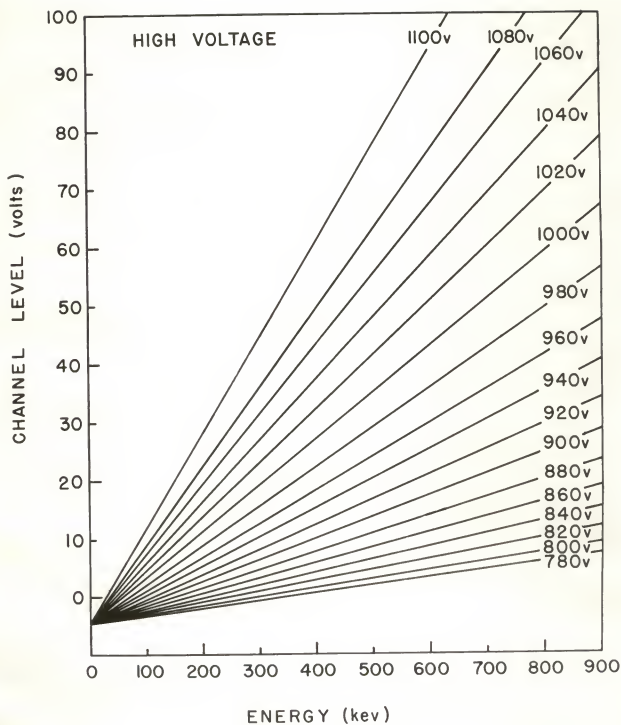as a parameter.

PLATE III
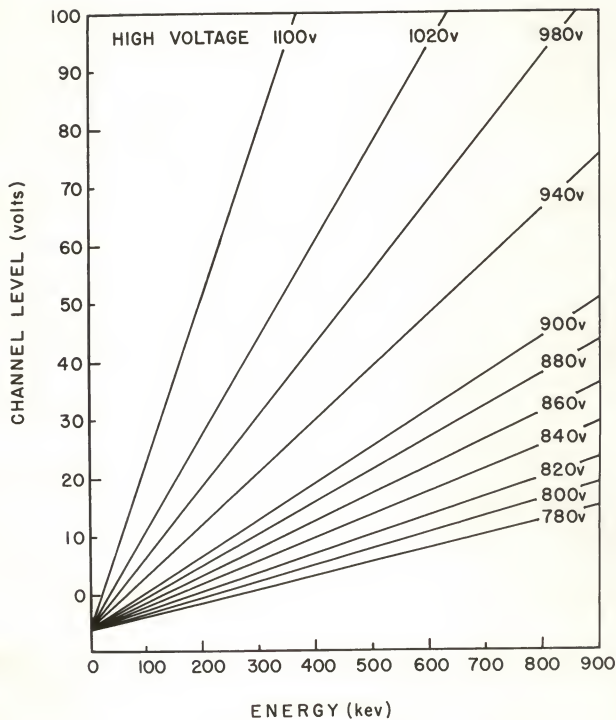
EXPLANATION OF PLATE IV

Graph showing the relation between the location and energy
of a gamma transition when the high voltage of the power supply,
used with the moveable crystal detector, is used as a parameter.

PLATE IV

Butler (3) p.23.

A shorter resolving time decreases the number of accidental coincidences and increases the ratio of true to accidental coincidences. However, the design of the pulse height selectors was such that the number of true coincidences recorded decreased as the resolving time was decreased. This feature has its origin in the rather large time delays built into the pulse height selector gating circuits, as discussed by Butler (3). Experiments were performed to determine the smallest value to which the resolving time could be decreased without increasing the loss of an appreciable number of true coincidences. Figure 1 is a graph showing the results as a plot of the differentiator knob setting versus the number of true coincidences. Since the source geometry and gamma-ray settings were held fixed in these tests, the figure shows that a choice of the shorter resolving time at knob setting 3 will not give rise to a loss of an appreciable number of true coincidences.
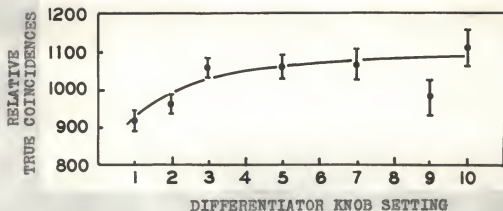

Fig. 1. Curve representing the change in the true coincidences as the differentiator knob setting is changed.

ANGULAR EFFICIENCY CURVES

Introduction

The variation of the coincidences with the position of
the moveable detector corresponds to the theoretical correlation
function $W(\alpha)$, equation (1), only under the assumption of
centered point sources[1] and ideal point detectors. Therefore,
before the experimentally determined coefficients may be compared
with the theoretical coefficients, a correction must be applied
for the finite solid angle of the detectors. After the finite
solid angle correction is applied to the theoretical correlation
function, the experimentally determined angular correlation
function is obtained and may be written as

$$(3) \qquad W(\alpha) = 1 + \sum_{k=1}^{m} (Q_{2k}/Q_0) A_{2k} P_{2k}(\cos\emptyset)$$

where $\emptyset$ denotes the angle between the crystal detector axes.
Each theoretical coefficient A_{2k} has been multiplied by the
appropriate geometry-efficiency factor Q_{2k} and the function
normalized by dividing by Q_0. Therefore, before the experi-
mentally determined coefficients can be compared with the
tabulated theoretical coefficients A_{2k} given by Rose and
Biedenharn (11), each coefficient, after the first, of equation
(3) must be divided by Q_{2k}/Q_0.

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[1]As mentioned previously the condition of a centered point
source was fulfilled.

The correction factors Q_{2k} may be written as

(4) $$Q_{2k} = J^1_{2k} J^2_{2k}$$

with

(5) $$J^i_{2k} = \int P_{2k}(\cos \phi) \epsilon^i(\theta) \sin \theta \, d\theta \qquad i = 1,2$$

where J^1_{2k} and J^2_{2k} refer to the moveable and fixed crystal detectors respectively. The integrals are evaluated over the polar angle subtended at the source by the face of the crystal, measured from the source to the crystal center as polar axis.

$\epsilon^i(\theta)$ denotes the angular efficiency of the ith crystal detector for a gamma-ray emitted at an angle θ with the longitudinal axis of the crystal detector.

Equation (5) has been given by Bertolini et al (1) and Frauenfelder and Lawson (8).

Collimation and Shielding

The data for the angular efficiency curves were obtained by means of a collimated beam of gamma-rays. The collimation was obtained by means of a lead block 12.5 cm long provided with a circular opening 1.9 mm in diameter. The source was inserted into the opening approximately 8 mm. The total width of the gamma-ray beam was less than 4°.

The effects of scattering were decreased by shielding the source and crystal detector with lead. The experimental arrangement is shown in Plate V.

EXPLANATION OF PLATE V

Diagram of the experimental arrangement used to obtain the
angular efficiency curves. The stippled portion of the diagram
represents the cross section of the lead shielding.

PLATE V
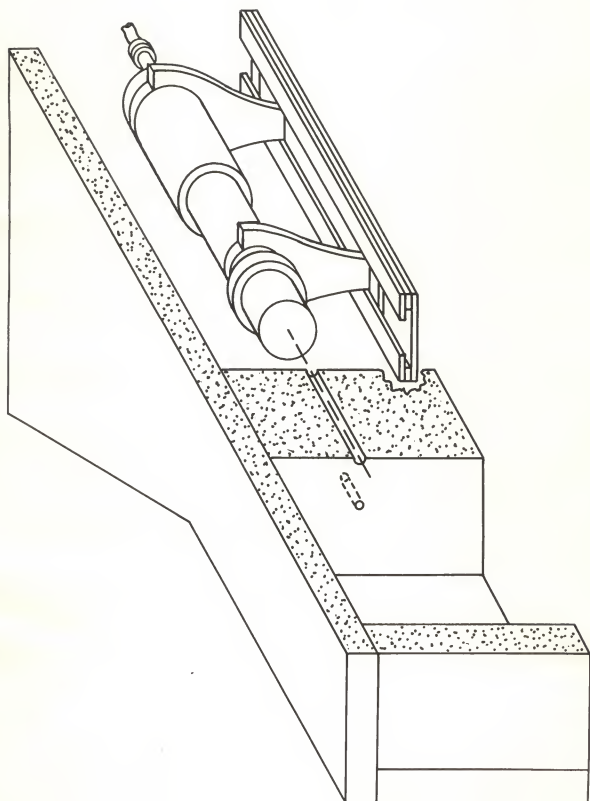
Collection and Treatment of Experimental Data

Since the efficiency $\epsilon^1(\theta)$ of the crystal detectors was a function of source-to-counter distance, efficiency curves were measured at both 6 and 8 cm where measurements of the angular correlation were to be taken. The efficiency of each crystal detector was measured for the particular gamma-ray energy which it would detect when angular correlation experiments were performed.

The gamma-ray energies which were to be detected by each of the crystal detectors when the 244-122 kev and 778-344 kev gamma cascades were investigated are listed in Tables 1 and 2.

Data for the efficiency curves were obtained by observing the change of the counting rate as the crystal detector, whose efficiency was to be measured, was rotated about the collimated source of gamma-rays in 5° increments. The crystal detector was then rotated 90° about its longitudinal axis and the above procedure repeated. The collimator was arranged so that the beam moved along the diameter of the face of the crystal as the detector was rotated.

In this way, two curves were obtained for each of the two source-to-counter distances using a specific gamma-ray energy. These curves will be designated as the rotated and unrotated efficiency curves.

The correction for background radiation was obtained by repeating the procedure for obtaining the efficiency curves but with the source inserted into the lead brick a short distance

from the collimator.

It was assumed that the efficiency of each crystal detector was cylindrically symmetrical. Experimentally there was found to be some variance and therefore an average efficiency curve for the crystal detector was used to numerically integrate equation (5). This average efficiency curve was obtained by using the average of the four experimental values, obtained from the data for the rotated and unrotated efficiency curves, over each 5° annular ring.

Results

Since both crystal detectors may not have the same source-to-counter distance, it was found more convenient to tabulate J_{2k}/J_0 for each crystal detector. The correction factors Q_{2k}/Q_0 may then be found by multiplication of the appropriate J_{2k}^1/J_0 and J_{2k}^2/J_0. This last statement can be clarified by use of an example; suppose the moveable detector is 8 cm from the source and detecting the 244 kev gamma-ray and the fixed detector is 6 cm from the source and detecting the 122 kev gamma-ray, then by use of Tables 1 and 2 below, Q_2/Q_0 may be found to be 0.897.

Tables 1 and 2 are a list of the experimental values obtained for J_{2k}/J_0 for the moveable and fixed detectors respectively. These tables extend only to J_2/J_0. Reference to these tables indicate that interpolations of the correction factors to other energies and source distances are reasonably safe.

Table 1. J_{2k}/J_0 for the moveable crystal detector.

Gamma-Ray Energy(kev)	Source-to-Counter Distance(cm)	J_2^1/J_0^1	J_4^1/J_0^1
244	6	0.937	0.801
778	6	0.947	0.834
244	8	0.964	0.879
778	8	0.965	0.890

Table 2. J_{2k}/J_0 for the fixed crystal detector.

Gamma-Ray Energy(kev)	Source-to-Counter Distance(cm)	J_2^2/J_0^2	J_4^2/J_0^2
122	6	0.931	0.794
344	6	0.938	0.804
122	8	0.960	0.871
344	8	0.962	0.882

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When an excited nucleus decays by the emission of two
gamma-rays in rapid succession there is found to be a correlation
between the directions of propagation of the quanta. This
correlation is described by a function $W(\alpha)$ which gives the
relative probability that the second quantum will be emitted
at an angle α with the first; $W(\alpha)$ is determined by the angular
momenta of the three nuclear levels involved in the two successive
transitions and by the multipole order of the radiation emitted
in these transitions. The angular correlation function may be
obtained experimentally by measuring the variation of the gamma-
gamma coincidence counting rates as the angle between the
crystal detectors is varied. The coefficients of the experi-
mentally determined correlation function can then be compared
with the tabulated theoretical coefficients to determine the
angular momenta of the three nuclear levels involved in the two
successive transitions.

The design and construction of the apparatus and source
holder, which were used with the coincidence spectrometer, for
the measurement of this variation in the coincidence counting
rates are discussed.

Parameter curves for both scintillation spectrometers are
presented. These curves were used to find, within a few tenths
of a channel level volt, where a gamma-ray of a particular energy
would be located as the high voltage of the power supply was
varied.

The steps taken to increase the stability of the scintilla-

tion spectrometers and the results of stability tests are discussed.

A shorter resolving time decreases the number of accidental coincidences. However, the design of the coincidence circuit, used with the two scintillation spectrometers for measuring the coincidence counting rates, was such that the number of true coincidences decreased as the resolving time decreased. A graph of the true coincidences versus the differentiator knob setting is presented to allow a choice of a shorter resolving time without the loss of an appreciable number of true coincidences.

The coefficients of the theoretical correlation function were calculated for ideal point detectors. A correction for the finite solid angle of the detectors must be applied to the experimentally determined coefficients before they can be compared with the tabulated theoretical coefficients.

The equations are presented for obtaining the solid angle correction factors. These equations were numerically integrated with the use of the experimentally determined angular efficiency curves.

The experimental arrangement and the collection and treatment of the angular efficiency curves are discussed.

The solid angle correction factors are tabulated for both crystal detectors for two source-to-counter distances and specific gamma-ray energies.